Recent Results from Belle

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(for the Belle Collaboration)

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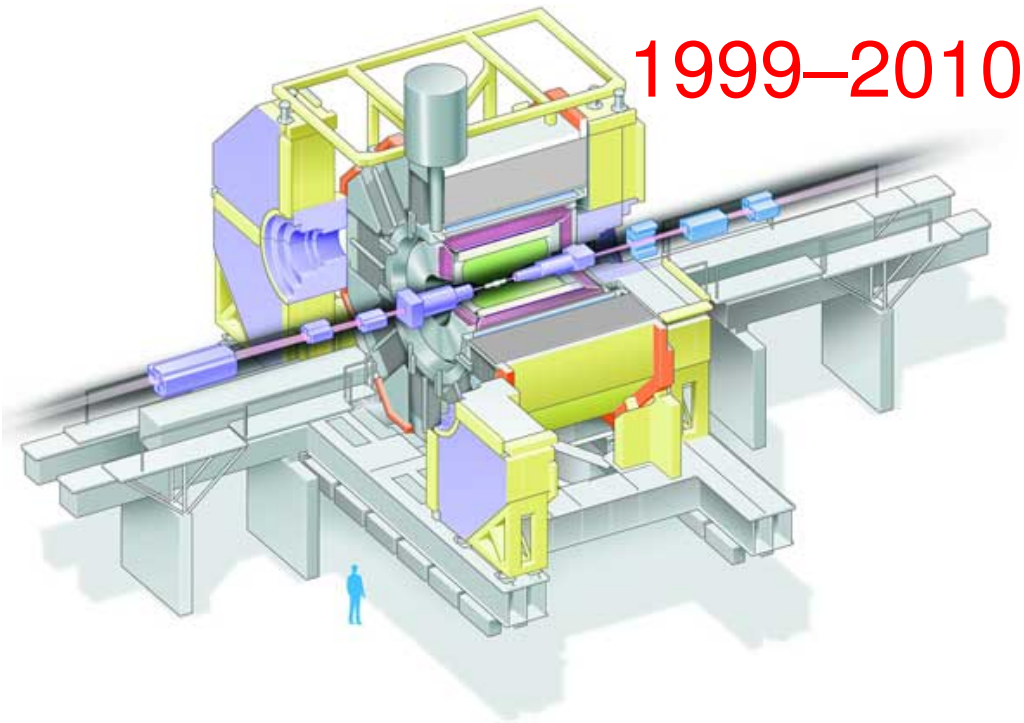
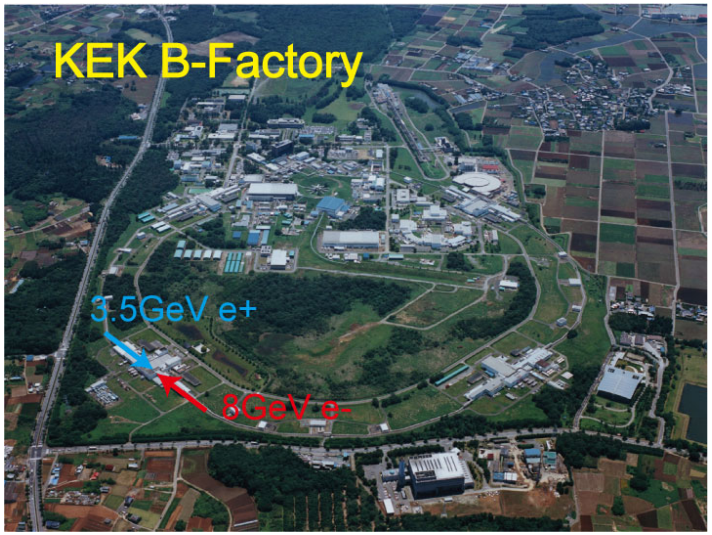
KEKB and Belle



1999–2010



Physics targets:

CP Violation,
Spectroscopy,
τ Physics,
New Physics beyond Standard Model,
...

Belle data samples:

On resonances:

$\Upsilon(5S)$:	121 fb^{-1}
$\Upsilon(4S)$:	711 fb^{-1}
$\Upsilon(3S)$:	3 fb^{-1}
$\Upsilon(2S)$:	25 fb^{-1}
$\Upsilon(1S)$:	5.8 fb^{-1}

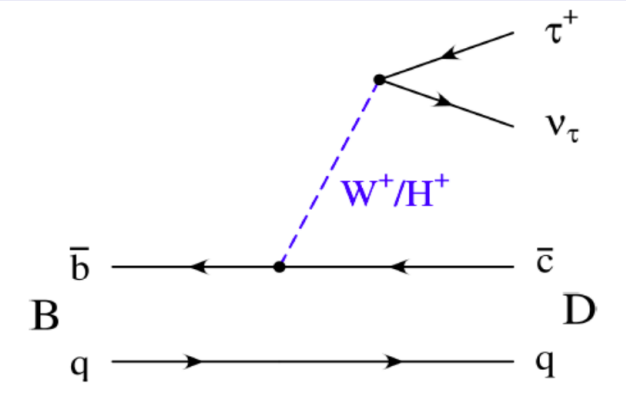
Off reson./scan:
$\sim$ 100 fb^{-1}
Total: $\sim$ 1000 fb^{-1}

Outline

1. Search for NP in $B \to D^{(*)}\tau\nu$
2. $A_{FB}(B \to X_s\ell^+\ell^-)$ with sum of exclusives
3. $e^+e^- \to b\bar{b}$ inclusive & exclusive

Search for NP in $B \to D^{(*)}\tau\nu$

- Process with third generation quarks and leptons
- In models with charged Higgs bosons their couplings are proportional to lepton mass, hence NP effects are enhanced for τ.



New Physics could change:

- Branching fraction
- τ polarizaion
- Effect could be different for D and D^*

BaBar result shows 3.4σ away from SM: PRL109, 101802(2012); PRD88, 072012(2013)

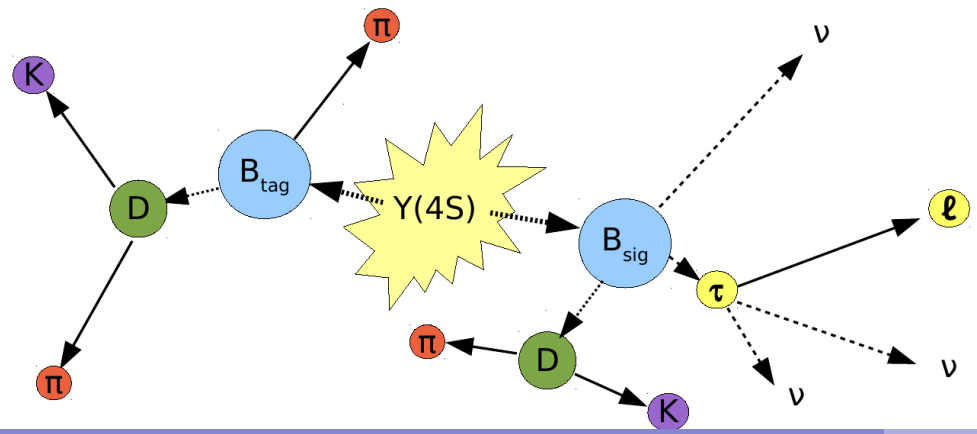
Experimental challenge:

2 (hadronic τ decay) or 3 (leptonic τ decay) undetected neutrinos

$$R = \frac{\mathscr{B}(B \to D\tau^-\bar{\nu}_\tau)}{\mathscr{B}(B \to Dl^-\bar{\nu}_l)}, \quad R^* = \frac{\mathscr{B}(B \to D^*\tau^-\bar{\nu}_\tau)}{\mathscr{B}(B \to D^*l^-\bar{\nu}_l)}; \quad l = e,\ \mu \tag{1}$$

Search for NP in $B \to D^{(*)}\tau\nu$

- Statistics: 772×10^6 $B\bar{B}$ pairs
- Selection:
  - B_{tag} is reconstructed using hadronic full reconstruction algorithm,
    which includes 1149 B final states ($\varepsilon_{rec}^{B^+} = 0.3\%$ and $\varepsilon_{rec}^{B^0} = 0.2\%$). Additional requirements on purity of B_{tag} sample preserves $\sim 85\%$ of signal $\bar{B} \to D^{(*)}\tau\nu$ decays
  - τ is reconstructed in the leptonic decays $\tau \to e\nu\nu, \mu\nu\nu$,
    so the signal and normalization modes have the same final particles $\to$ reduces systematic uncertainty of $R^{(*)}$
  - In the events with B_{tag} we select $D^{(*)}l$ ($D^+l^-, D^0l^-, D^{*+}l^-, D^{*0}l^-$), $l = e$ *or* μ among remaining trackgs and clusters:
    - $D^+ \to K^-\pi^+\pi^+$, $K_s^0\pi^+$, $K_s^0\pi^+\pi^0$, $K_s^0\pi^+\pi^-\pi^+$; $D^{*+} \to D^0\pi^+$, $D^+\pi^0$;
    - $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, $K_s^0\pi^0$, $K_s^0\pi^+\pi^-$; $D^{*0} \to D^0\pi^0$, $D^0\gamma$;
    - $-0.2 < M_{\rm miss}^2 < 8.0\ ({\rm GeV}/c^2)^2$, $M_{\rm miss}^2 = (P_{beam} - P_{B_{tag}} - P_{D^{(*)}} - P_l)^2$;
    - $q^2 > 4{\rm GeV}^2/c^2$, $q^2 = (P_B - P_{D^{(*)}})^2$; $\to$ suppress semileptonic B decays



arXiv: 1507.03233.
Accepted by PRD.

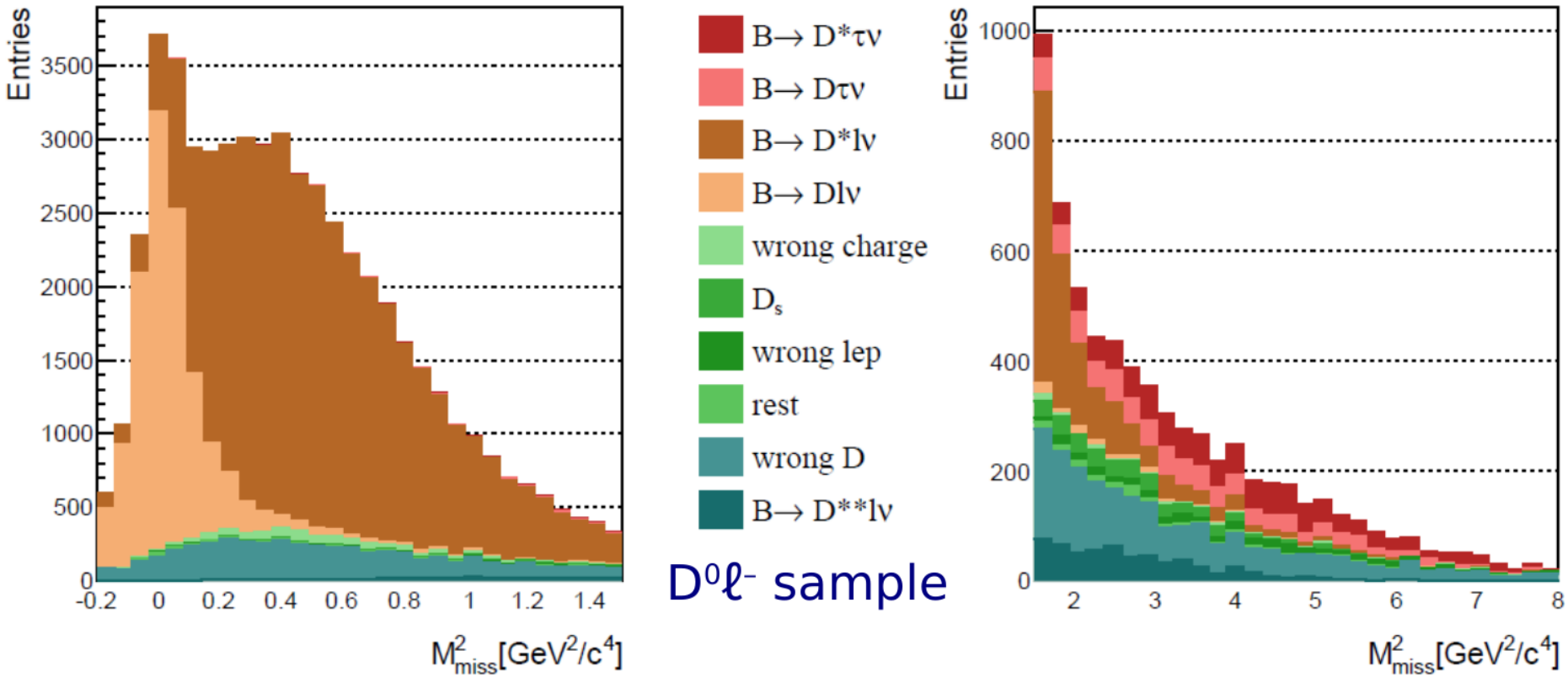
Search for NP in $B \to D^{(*)}\tau\nu$

$M^2_{\rm miss}$ range is split into two regions:

1. $M^2_{\rm miss} < 0.85\ ({\rm GeV}/c^2)^2$: populated by events of $B \to D^{(*)}e\nu_e,\ D^{(*)}\mu\nu_\mu$
2. $M^2_{\rm miss} > 0.85\ ({\rm GeV}/c^2)^2$: enriched by $B \to D^{(*)}\tau\nu_\tau$ ($\tau \to e\nu_e\nu_\tau,\ \mu\nu_\mu\nu_\tau$)

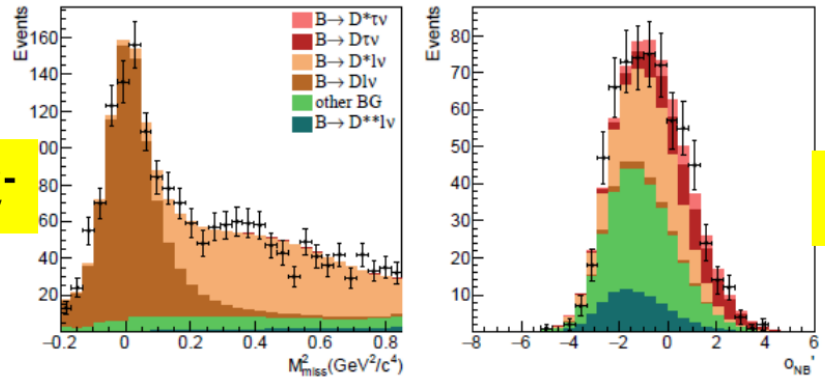
Simultaneous fit to both regions.

- To constrain $B \to D^{(*)}e\nu,\ D^{(*)}\mu\nu$ yields, fit on $M^2_{\rm miss}$ (peak at zero).
- Region(2), some bkg like $B \to D^{**}l\nu$ has $M^2_{\rm miss}$ and yield similar to τ signal. So fit this region on neural network output (O_{NB}).

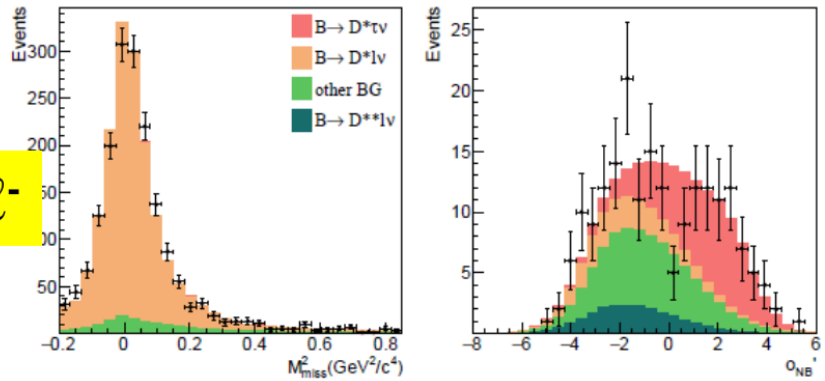


Fit results

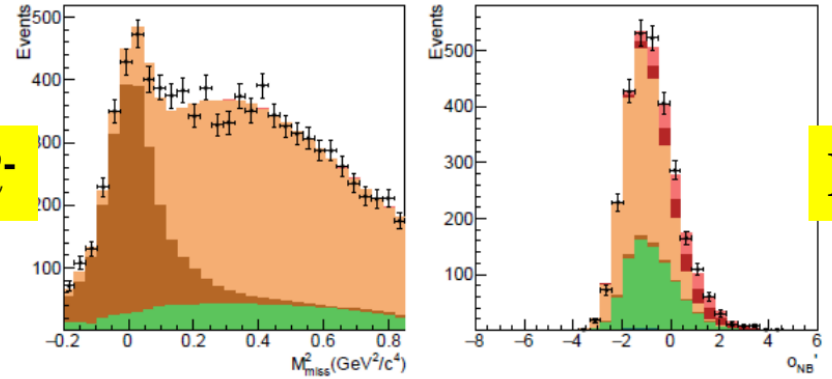
$D^+\ell^-$



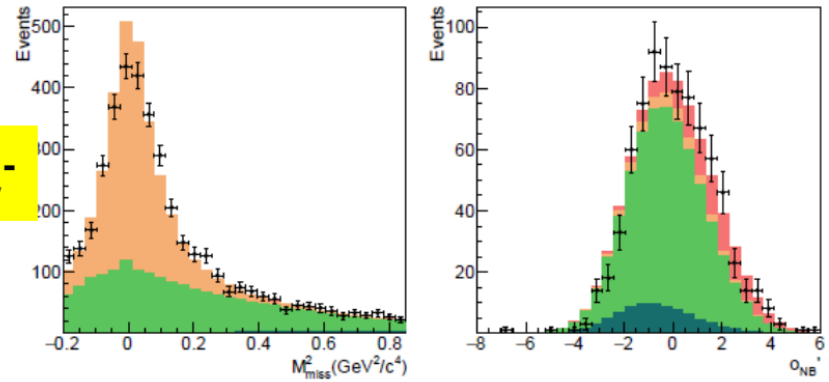
$D^{*+}\ell^-$



$D^0\ell^-$



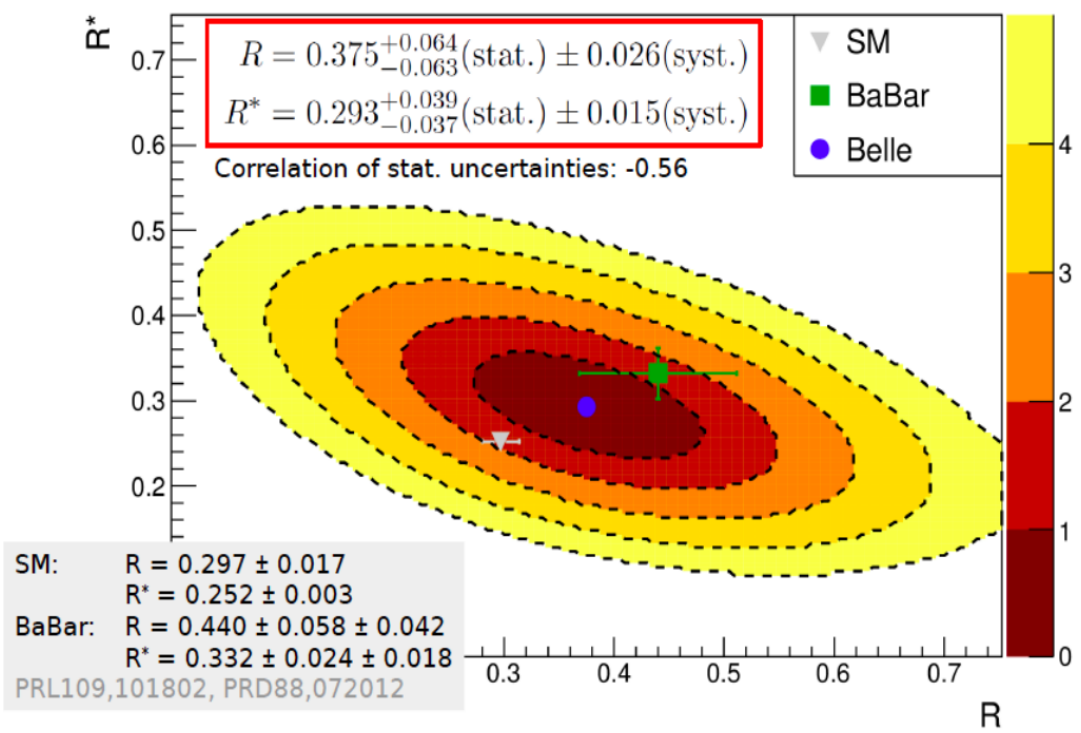
$D^{*0}\ell^-$

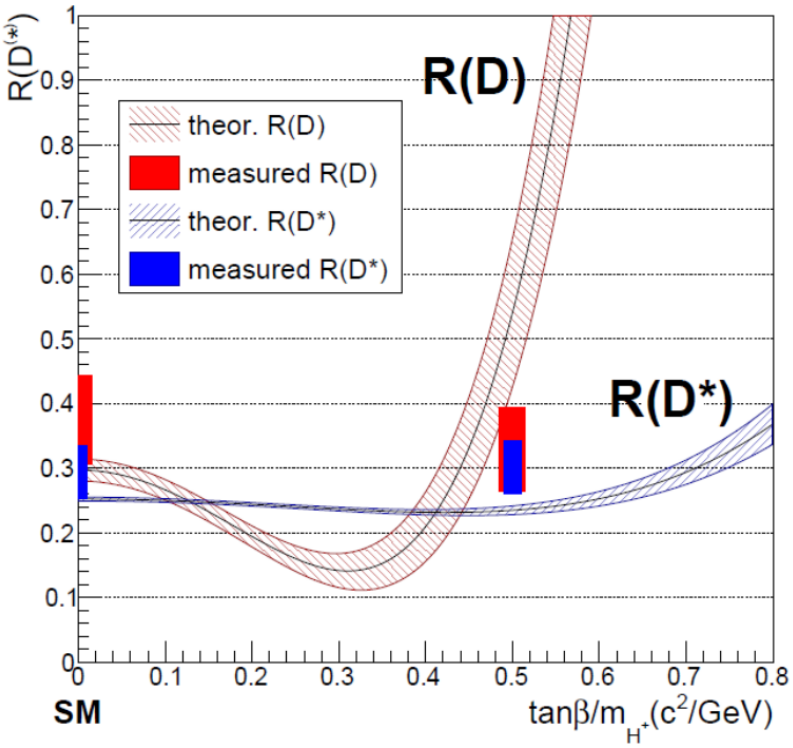


$$O'_{\mathrm{NB}} = \ln \frac{O_{\mathrm{NB}} - O_{min}}{O_{max} - O_{\mathrm{NB}}}$$

arXiv: 1507.03233.

Results and NP in $B \to D^{(*)}\tau\nu$



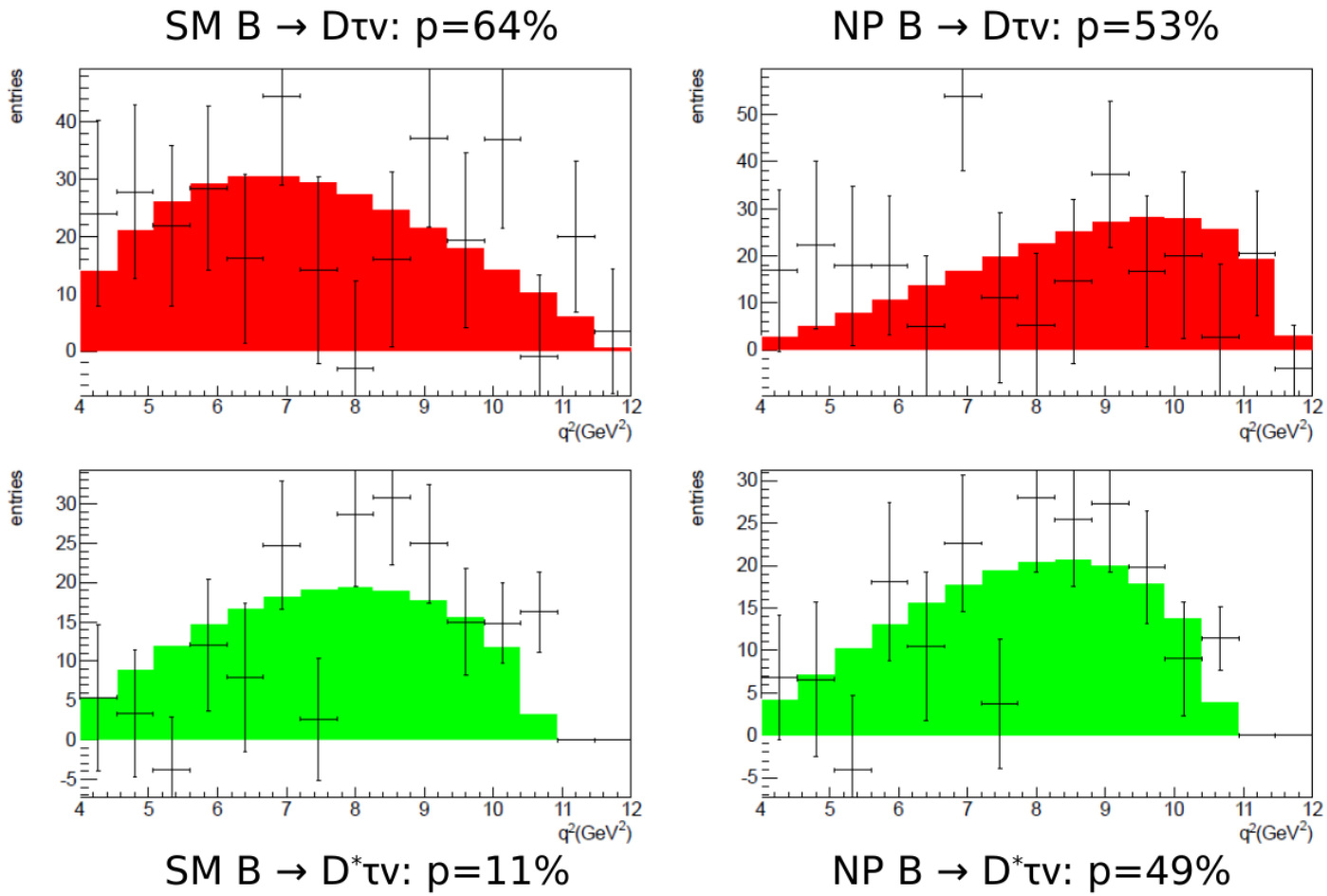


- $R(D) = 0.329 \pm 0.060 \pm 0.022$; $R(D)_{2HDM} = 0.590 \pm 0.125$
- $R(D^*) = 0.301 \pm 0.039 \pm 0.015$; $R(D^*)_{2HDM} = 0.241 \pm 0.007$

Belle result compatible with 2HDM type II model in the region around $tan\beta/M_{H^\pm} = 0.45\ (\text{GeV}/c^2)^{-1}$ and zero.

arXiv: 1507.03233.

And the q^2 Spectrum



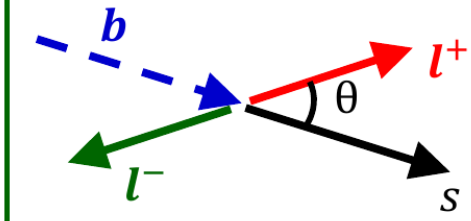
- The $D^+ l^-$ and $D^0 -$ samples and the $D^{*+} l^-$ and $D^{*0} -$ samples are combined to increase statistics.
- NP: Type-II 2HDM result with $tan\beta / M_{H^\pm} = 0.5\ (\mathrm{GeV}/c^2)^{-1}$
- A χ^2 test shows that both hypotheses are compatible with Belle data.

arXiv: 1507.03233.

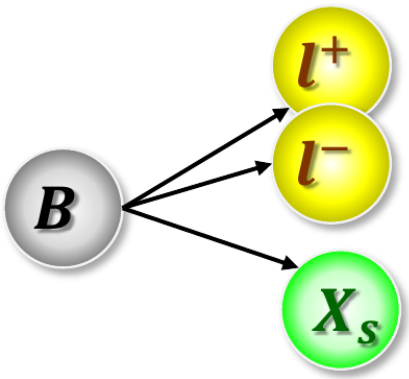
$A_{FB}(B \to X_s \ell^+ \ell^-)$ with sum of exclusives

- Forward-backward Asymmetry (A_{FB}) can be expressed with three Wilson coefficients (C_7, C_9, C_{10}).

$$A_{FB} \equiv \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \propto -\mathrm{Re}\left[\left(2C_7^{eff} + \frac{q^2}{m_b^2} C_9^{eff}\right) C_{10}^{*}\right]$$



@ di-lepton rest frame



l^+l^-: e^+e^- or $\mu^+\mu^-$

$X_s := K^{\pm}/K_S$ + up to 4π (at most $1\pi^0$)

[K]	K, K_S
[$K\pi$]	$K\pi$, $K_S\pi$, $K\pi^0$, $K_S\pi^0$
[$K2\pi$]	$K2\pi$, $K_S2\pi$, $K\pi\pi^0$, $K_S\pi\pi^0$
[$K3\pi$]	$K3\pi$, $K_S3\pi$, $K2\pi\pi^0$, $K_S2\pi\pi^0$
[$K4\pi$]	$K4\pi$, $K_S4\pi$, $K3\pi\pi^0$, $K_S3\pi\pi^0$

$M_{X_s} < 2.0$ GeV/c^2

- $b \to s\ell^+\ell^-$ is studied to search for New Physics.
- 10 flavor specific states for A_{FB} measurement ($\sim$ 50% of total).
- Neural network for suppression of continuum and $B\bar{B}$ semileptonic bkg.
- Veto Charmonium: J/ψ and $\psi(2S)$.

arXiv: 1402.7134

Signal extraction

- Divide data into 4 q^2 regions to perform a fit.
- Correct A_{FB}^{raw} to A_{FB}^{true}.

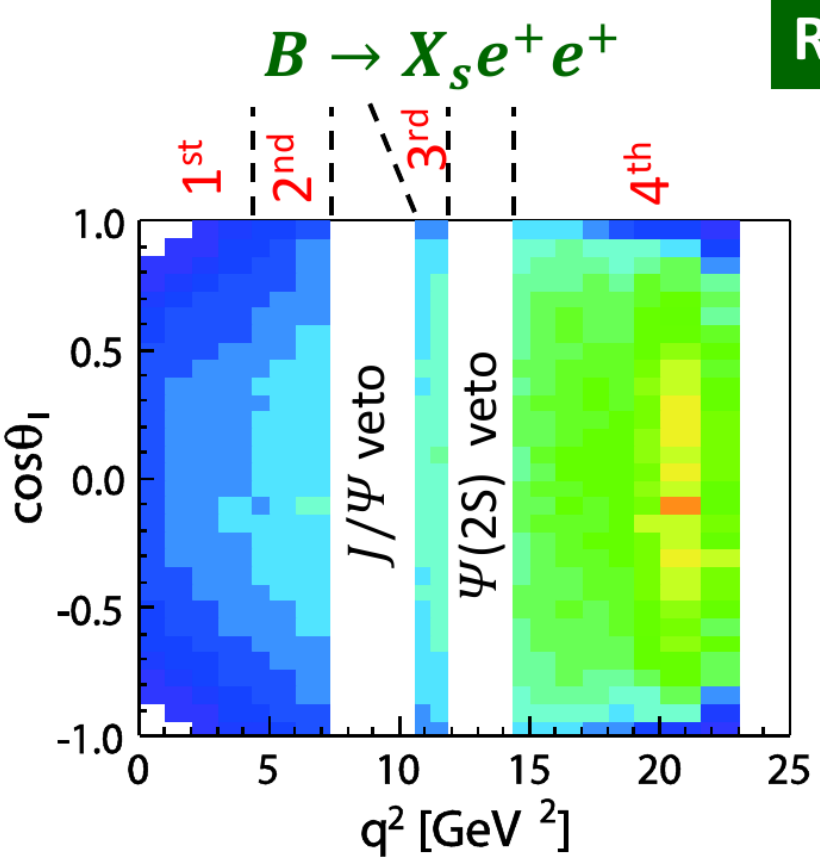
$$A_{\mathrm{FB}}^{\mathrm{true}} = \alpha^{\mu\mu} \times A_{\mathrm{FB}}^{\mathrm{raw},\mu\mu} = \alpha^{ee} \times \beta \times A_{\mathrm{FB}}^{\mathrm{raw},ee}$$

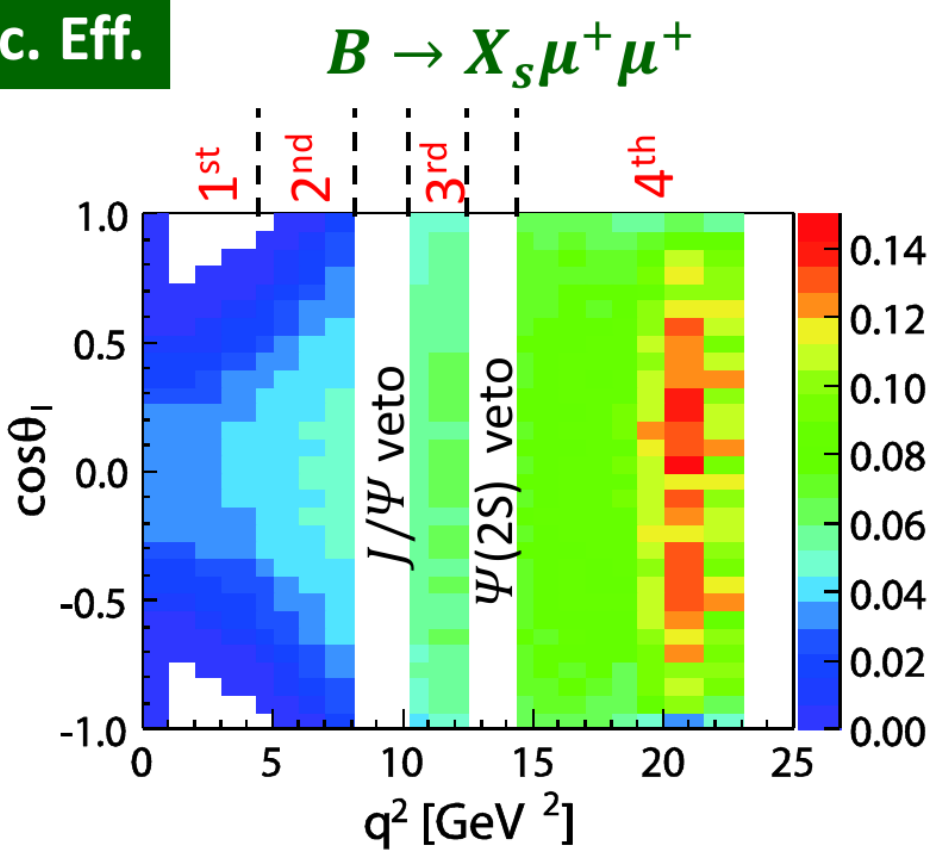
α : scale factor due to rec. efficiency

β : correction due to different Charmonium veto range.

– α is derived using MC with various sets of C_7, C_9, C_{10}.

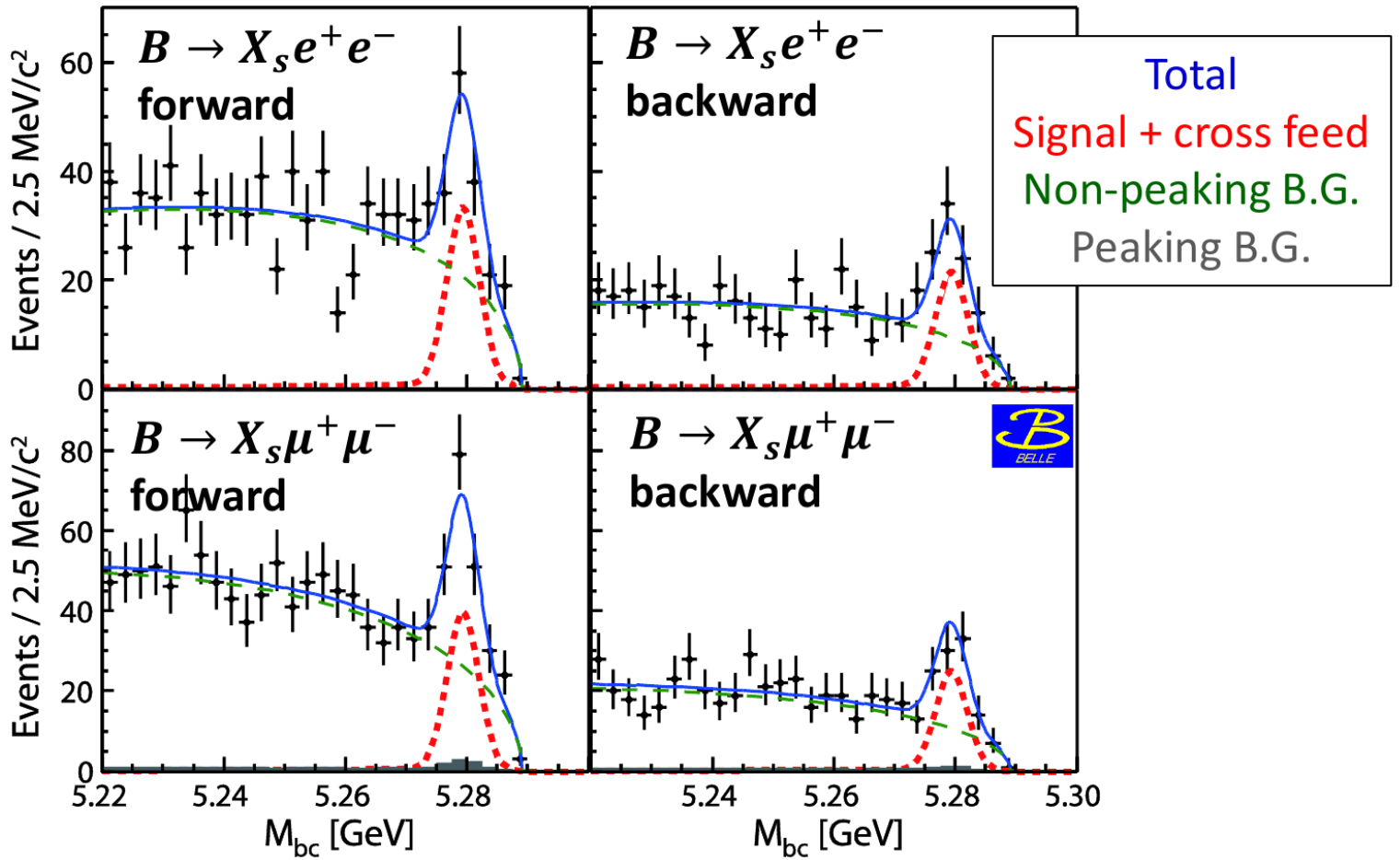
Rec. Eff.





Fitting for $A_{FB}(B \to X_s \ell^+ \ell^-)$

- Unbinned maximum likelihood fit to M_{bc} for each q^2 bin: positive/negative $\cos\theta$, $e^+e^-/\mu^+\mu^-$.

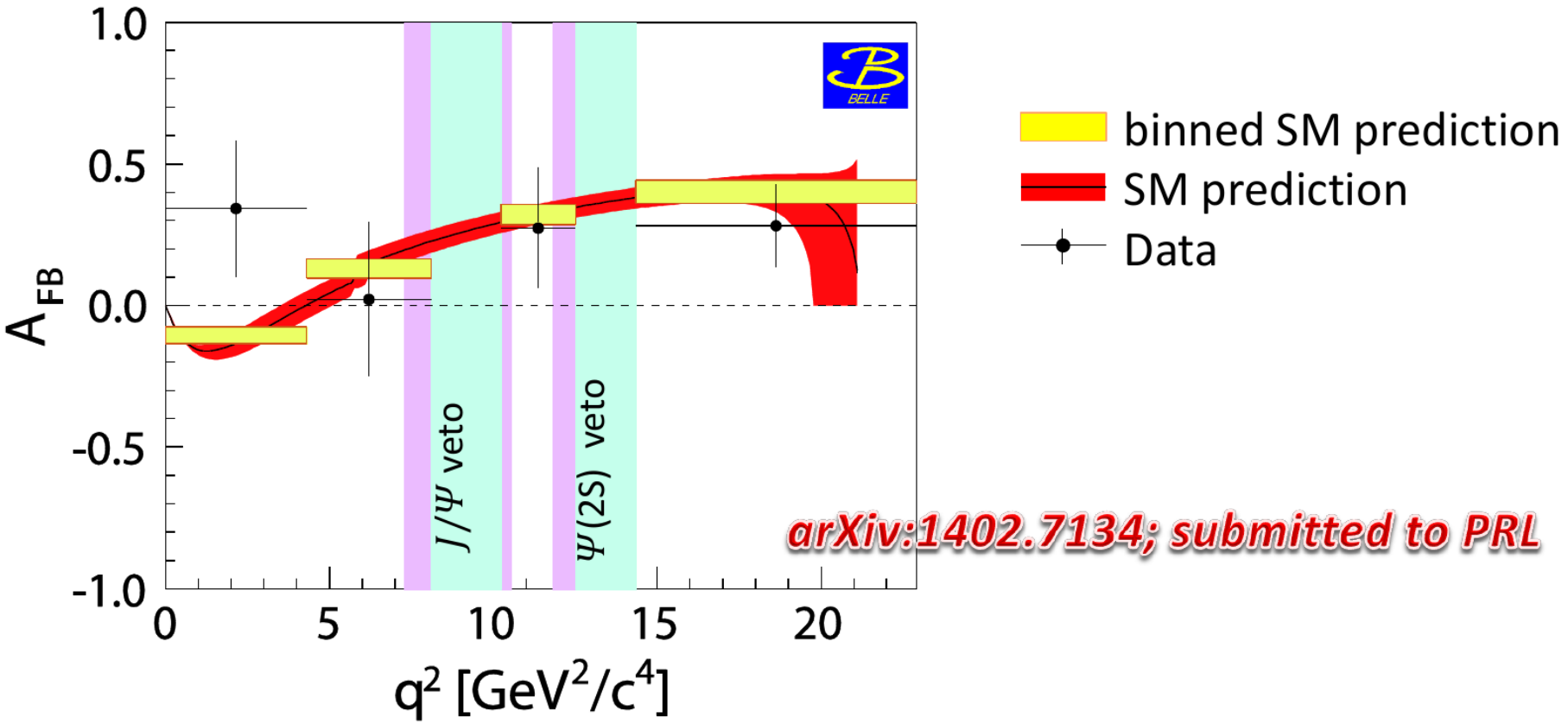


- Dominant systematics
  –α correction, peaking bkg.

1. Leakage from $B \to J/\psi(\psi(2S))X_s$ veto.
2. Double mis ID from $B \to D^{(*)}n\pi$.
3. Swapped mis ID in $B \to J/\psi(\psi(2S))X_s$.

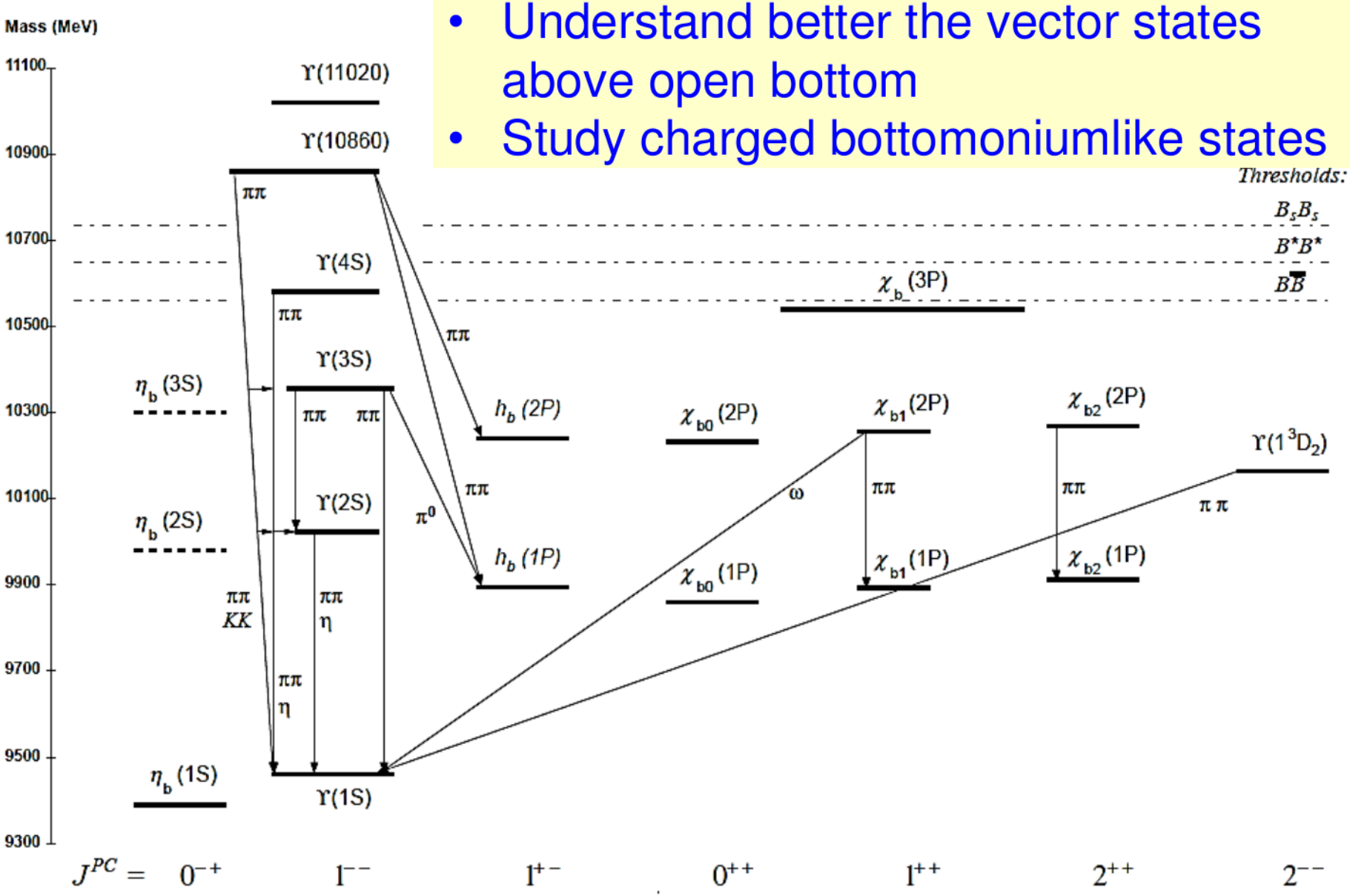
Result of $A_{FB}(B \to X_s \ell^+ \ell^-)$

- A_{FB} are consistent with SM.
  - The deviation of the 1^{st} bin ($q^2 < 4.3\mathrm{GeV}^2/c^2$) is 1.8σ.
  - Exclude $A_{FB} < 0$ at $q^2 > 10.2\ \mathrm{GeV}^2/c^2$ at 2.3σ.
- First measurement of inclusive A_{FB} with sum-of-exclusives



$e^+e^- \to b\bar{b}$ inclusive & exclusive

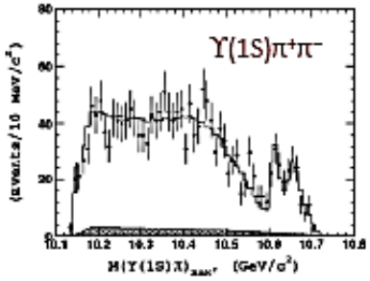
- Understand better the vector states above open bottom
- Study charged bottomoniumlike states

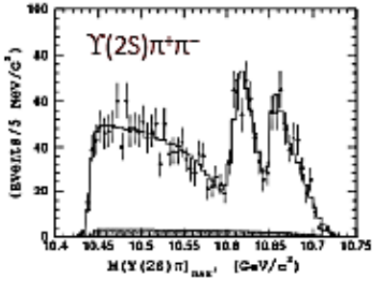


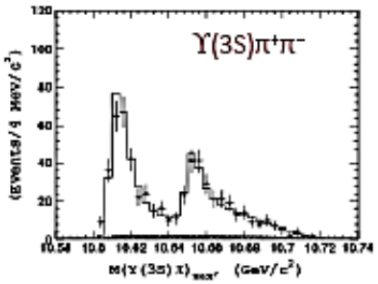
Previous results on Z_b states

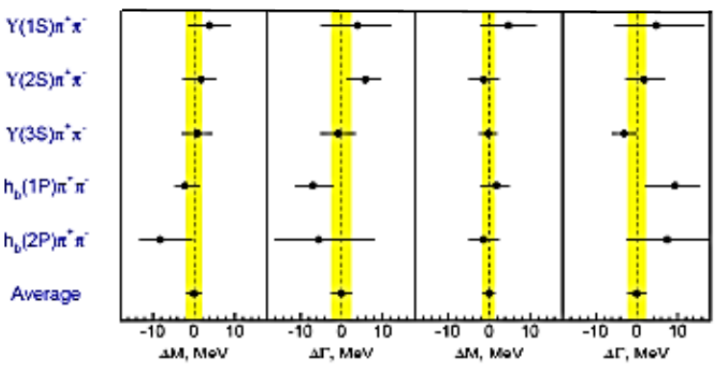
$Z_b^{\pm}$ observed in five different modes:

PRL108, 122001(2012)





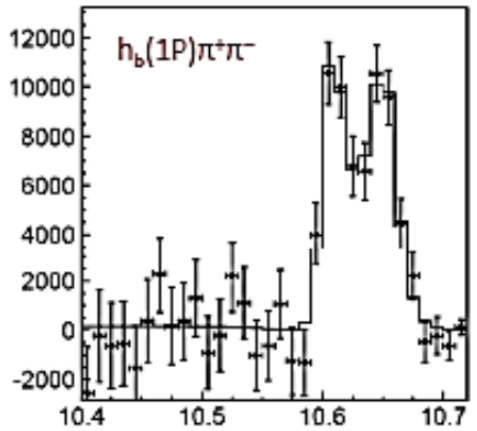


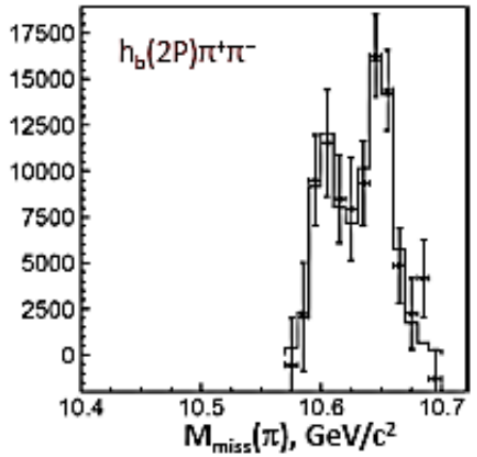


Average for $Z_b^{\pm}$:

$$\langle M_1 \rangle = 10607.2 \pm 2.0 \text{ MeV}$$
$$\langle \Gamma_1 \rangle = 18.4 \pm 2.4 \text{ MeV}$$

$$\langle M_2 \rangle = 10652.2 \pm 1.5 \text{ MeV}$$
$$\langle \Gamma_2 \rangle = 11.5 \pm 2.2 \text{ MeV}$$

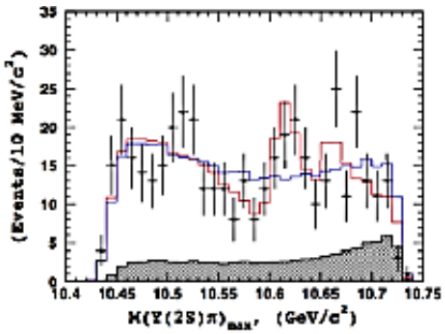




Z_b^0 Results:

$$\langle M_1 \rangle = 10609 \pm 7 \pm 6 \text{ MeV}$$

Consistent with $Z_b^{\pm}$



- $M_{Z_{b1}} - M_B - M_{B^*} = 2.4 \pm 2.1 \text{ MeV}/c^2$
- $M_{Z_{b2}} - M_{B^*} - M_{B^*} = 1.8 \pm 1.8 \text{ MeV}/c^2$

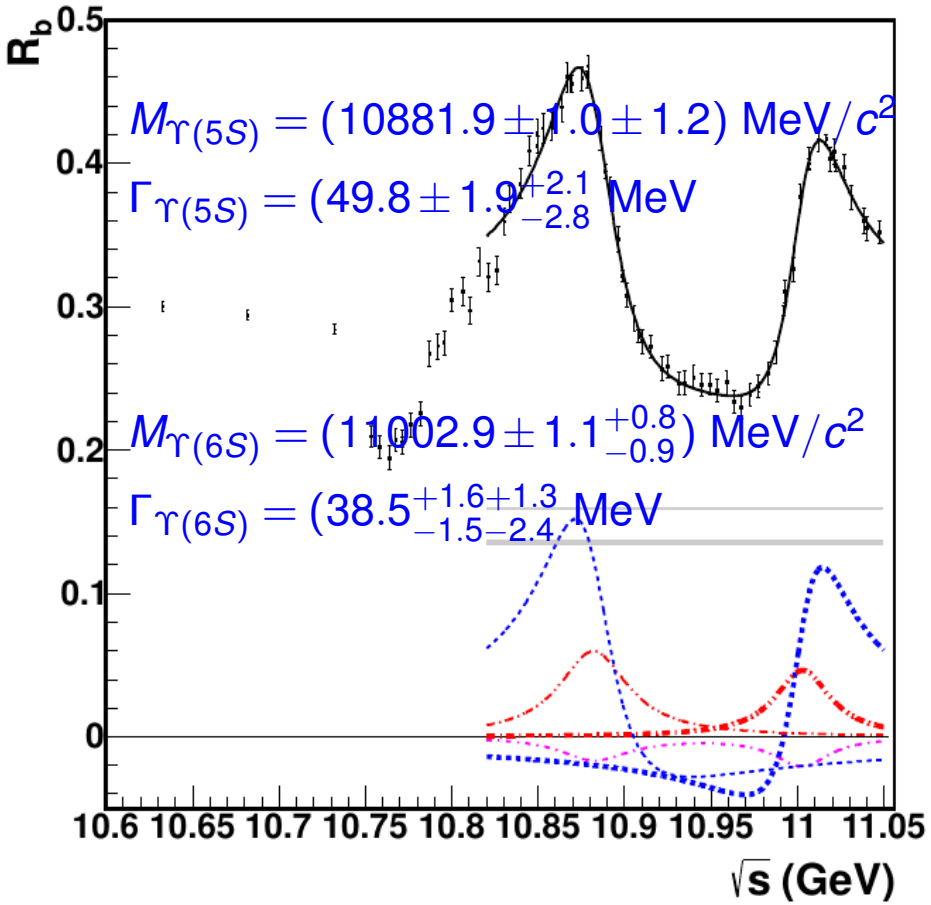
$$R_b = \frac{\sigma(e^+e^- \to b\bar{b})}{\sigma^0(e^+e^- \to \mu^+\mu^-)}$$

$$\mathscr{F} = |A_{nr}|^2 + |A_r + A_{5S}e^{i\phi_{5S}}f_{5S} + A_{6S}e^{i\phi_{6S}}f_{6S}|^2$$

Procedure:

1. Count hadronic events
2. Subtract scaled cont. (udsc)
3. Subtract ISR $\Upsilon(1S, 2S, 3S)$
4. Do efficiency correction
5. Divided by lum & $\sigma^0(\mu^+\mu^-)$

- No ISR corr.; no VP corr.
- Fit with constant width BW in small energy range.
- Need better model to fit



Agree with BaBar [PRL102,012001(2009)] with improved precision

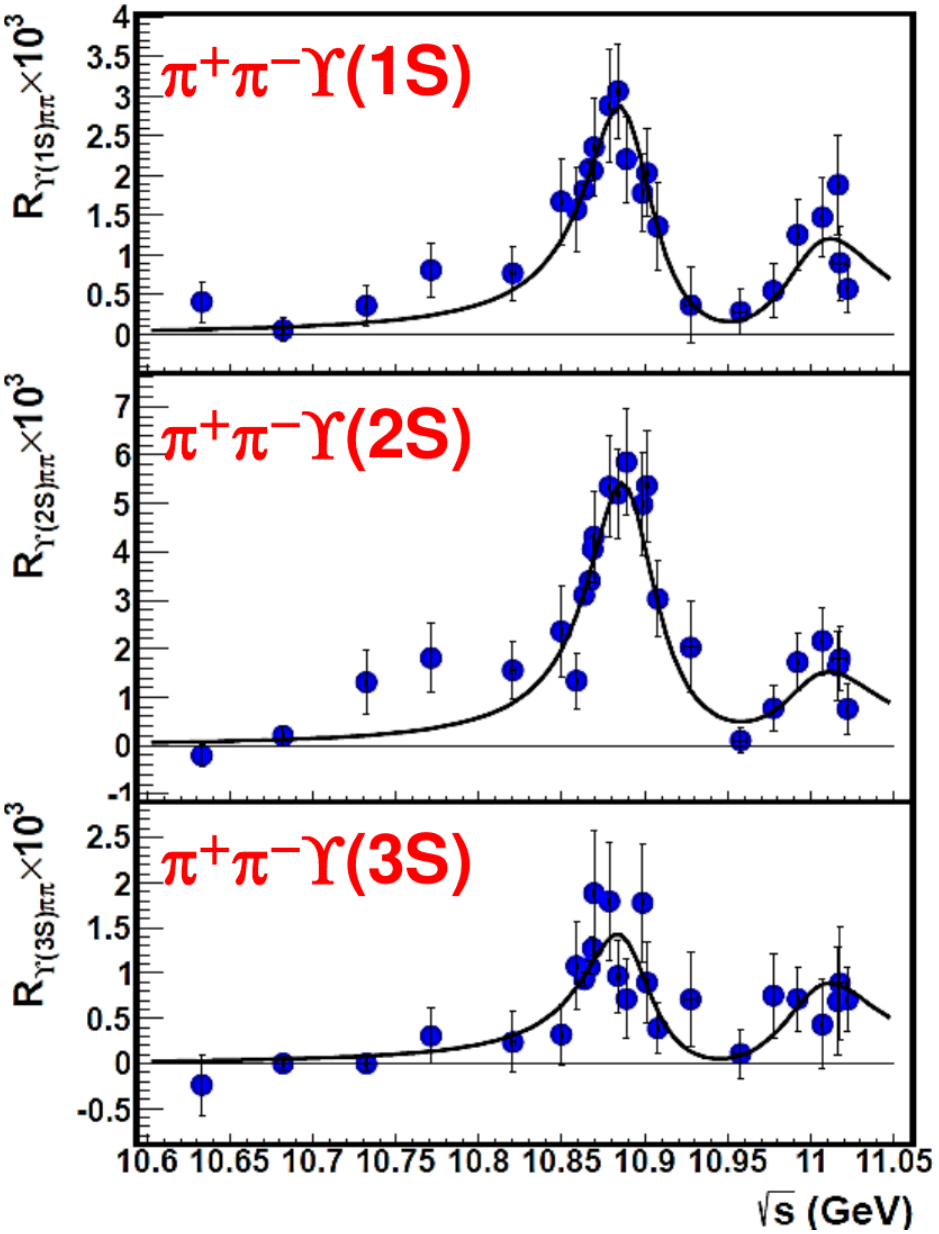
$E_{cm} = 10.54 - 11.20$ GeV, 5 MeV step for > 300 points, 3.9 fb^{-1} in total

arXiv: 1501.01137

$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

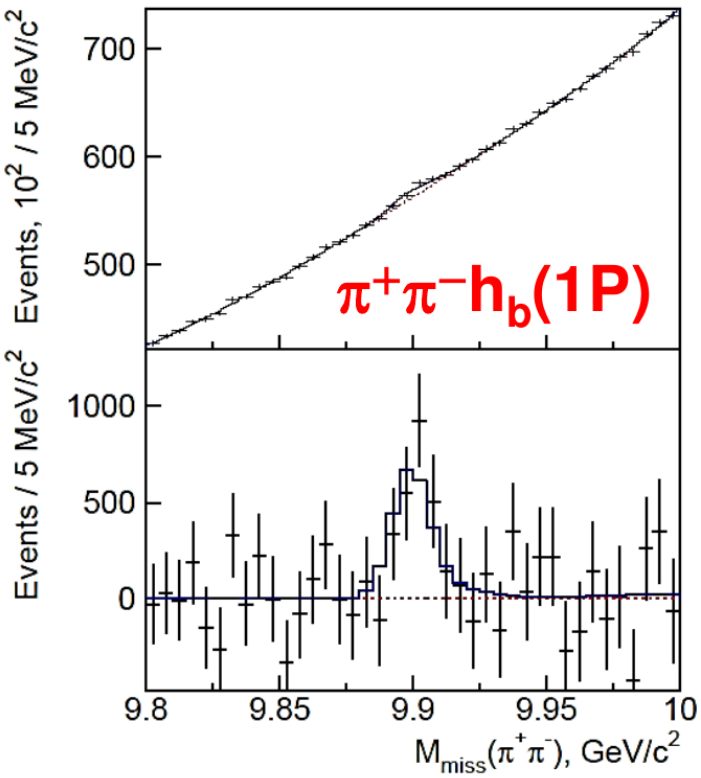
- tag $\Upsilon(nS) \to \mu^+\mu^-$ and select $\pi^+\pi^-$, fit to $|A_{5S} + e^{i\phi}A_{6S}|$
- $\Upsilon(5S)$
  - $M = (10891.9 \pm 3.2^{+0.6}_{-1.5})$ MeV/c^2
  - $\Gamma = (53.7^{+7.1+0.9}_{-5.6-5.4}$ MeV)
- $\Upsilon(6S)$
  - $M = (10987.5^{+6.4+2.2}_{-2.5-2.1})$ MeV/c^2
  - $\Gamma = (61^{+9+19}_{-2-20}$ MeV)
- Results agree with previous measurements
- Also agree with fit with R_b reasonably well
- Still room for improvement

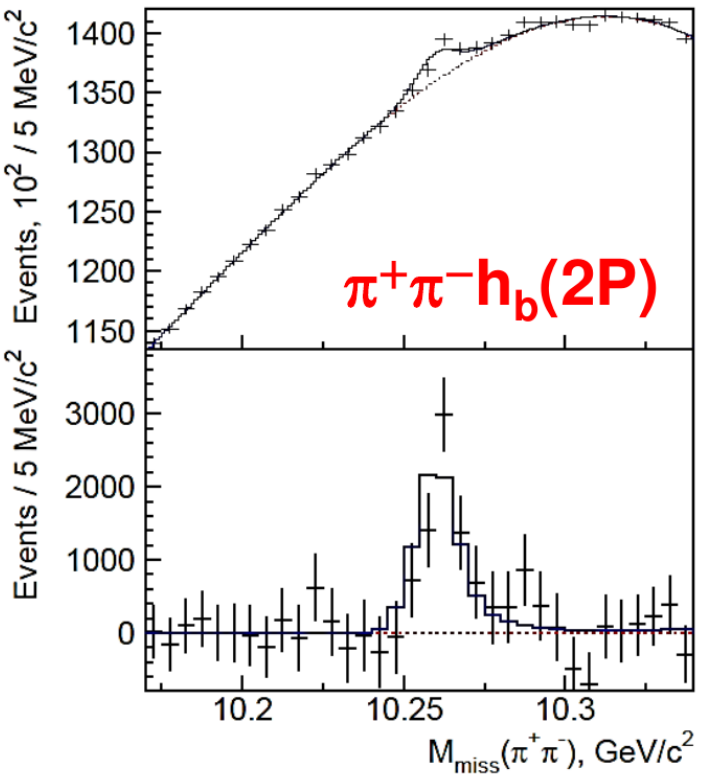
arXiv: 1501.01137



$e^+e^- \to \pi^+\pi^- h_b(nP)$

- Reconstruct $\pi^+\pi^-$, require π^+/π^- recoil mass in Z_b region: $10.59 < M^2_{\rm miss}(\pi) < 10.67\ {\rm GeV}/c^2$
- check the $\pi^+\pi^-$ recoil mass for $h_b(nP)$





arXiv: 1508.06562

$e^+e^- \to \pi^+\pi^- h_b(nP)$

$A_n f(s)|BW_{5S} + a \cdot e^{i\phi} BW_{6S} + b \cdot e^{i\delta}|$

$\Upsilon(5S)$

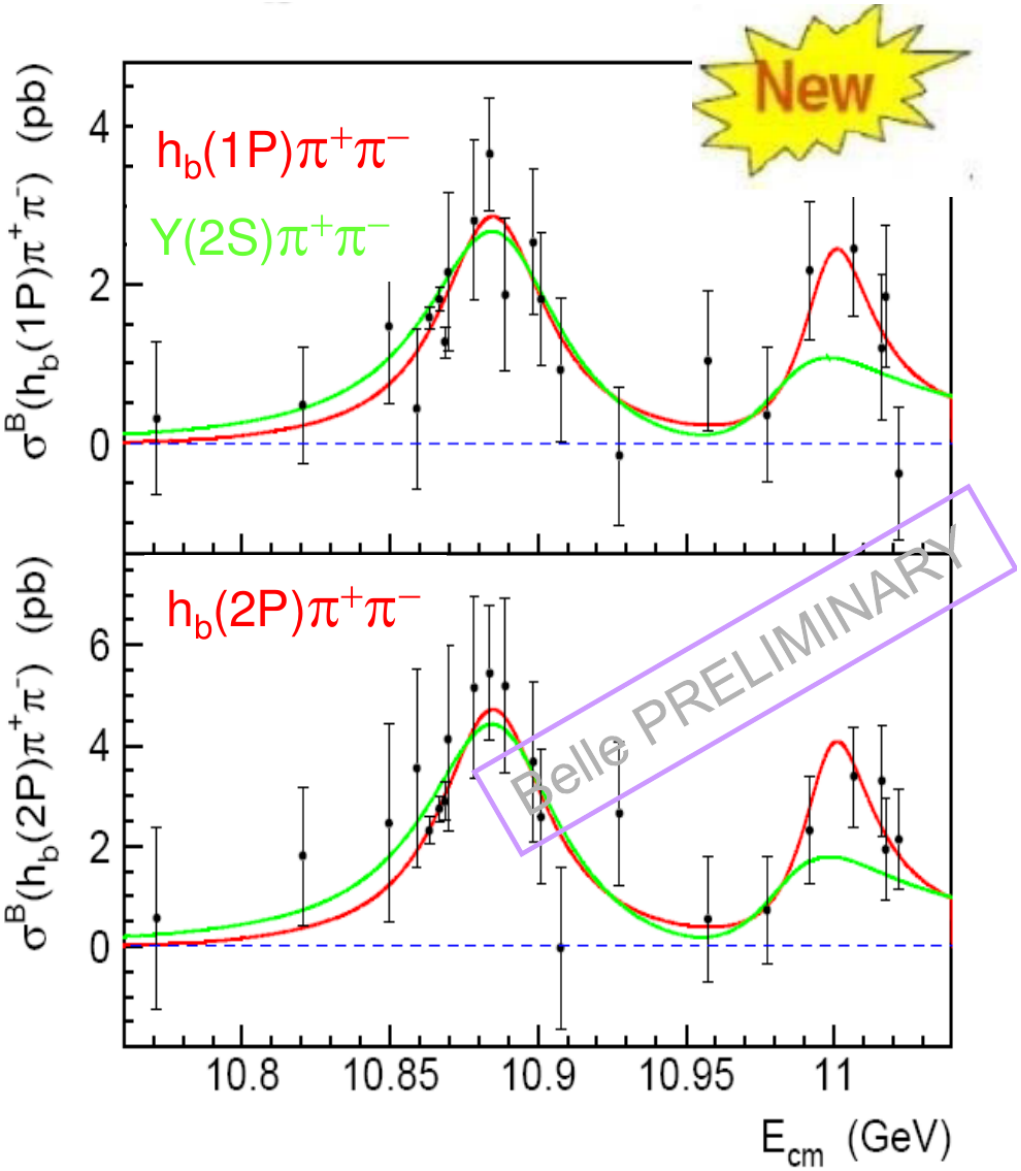
- $M = (10884.7^{+3.2+8.6}_{-2.9-0.6})$ MeV/c^2
- $\Gamma = (44.2^{+11.9+2.2}_{-7.8-15.8})$ MeV

$\Upsilon(6S)$

- $M = (10998.6 \pm 6.1^{+16.1}_{-1.1})$ MeV/c^2
- $\Gamma = (29^{+20+2}_{-12-7})$ MeV

$a = 0.64^{+0.37+0.13}_{-0.11-0.0}$

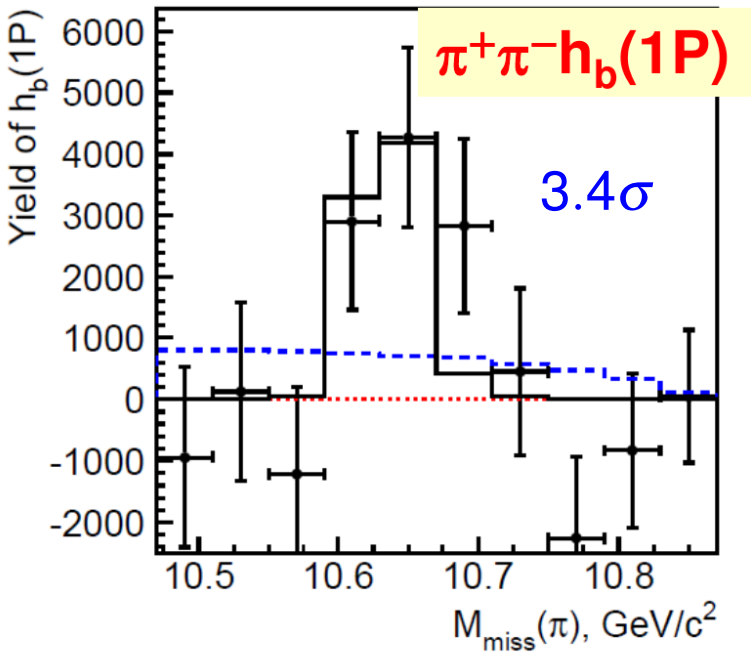
- Resonant parameters agree with those from $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$
- $e^+e^- \to \pi^+\pi^- h_b(nP)$ at the same level as $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$
- 1^{st} obs. of $\Upsilon(6S) \to \pi^+\pi^- h_b(nP)$

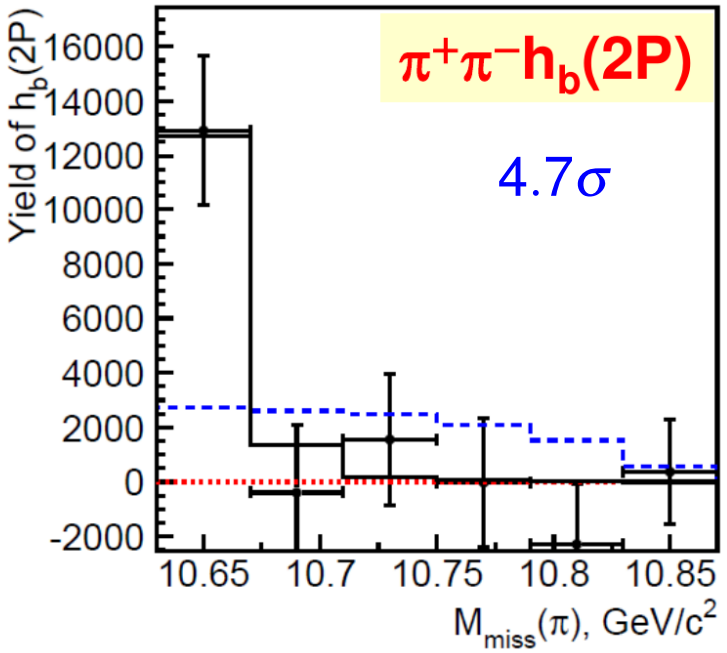


arXiv: 1508.06562

Z_b in $e^+e^- \to \pi^+\pi^- h_b(nP)$

- Events mainly from Z_b intermediate states, not clear if only one Z_b or both.
- Belle II will tell us.





- An evidence of $\Upsilon(6S) \to Z_b(\to h_b\pi)\pi$.

arXiv: 1508.06562

Summary

- $B \to D^{(*)}\tau\nu$ have been studied at Belle
  - Results on R and R^* agree with both SM expectation and BaBar results.
  - It is also consistent with 2HDM type-II model in the region around $tan\beta/M_{H^\pm} = 0.5\ (\mathrm{GeV}/c^2)^{-1}$
- $A_{FB}(B \to X_s\ell^+\ell^-)$ with sum-of-exclusives
  - Exclusive $A_{FB} < 0$ at $q^2 > 10.2\ \mathrm{GeV}^2/c^2$ at 2.3σ.
  - First measurement of inclusive A_{FB} with sum-of-exclusives
- $e^+e^- \to b\bar{b}$ inclusive & exclusive
  - improved knowledge on $\Upsilon(5S)$ and $\Upsilon(6S)$
  - $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ and $\sigma(e^+e^- \to h_b(nP)\pi^+\pi^-$ are similar.
  - An evidence of $\Upsilon(6S) \to Z_b(\to h_b\pi)\pi$.

Thank you!

Backup

Neural Network

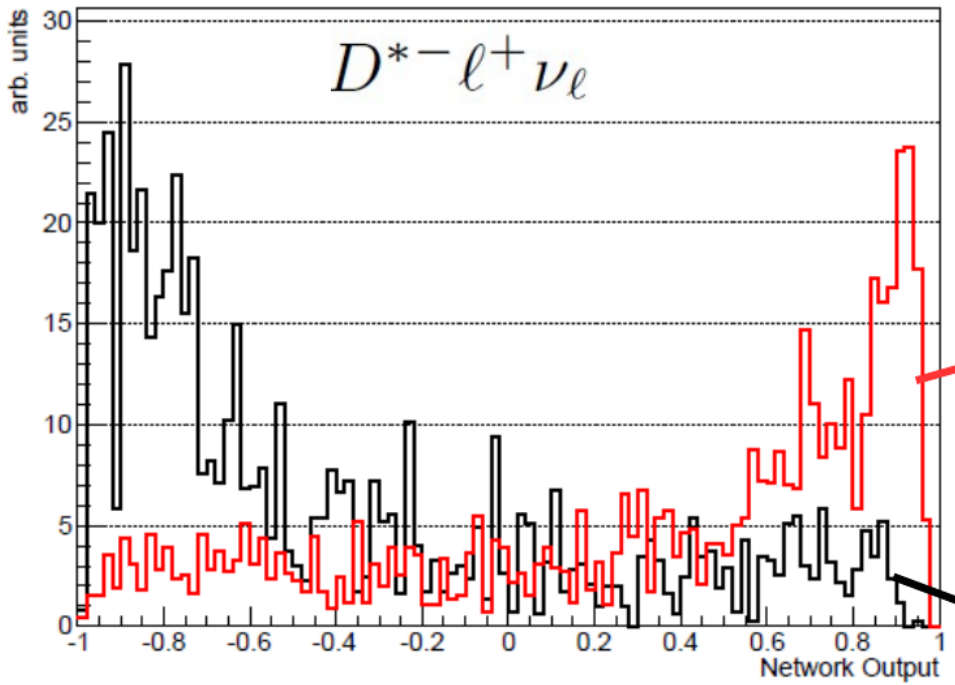
One network per reconstruction sample

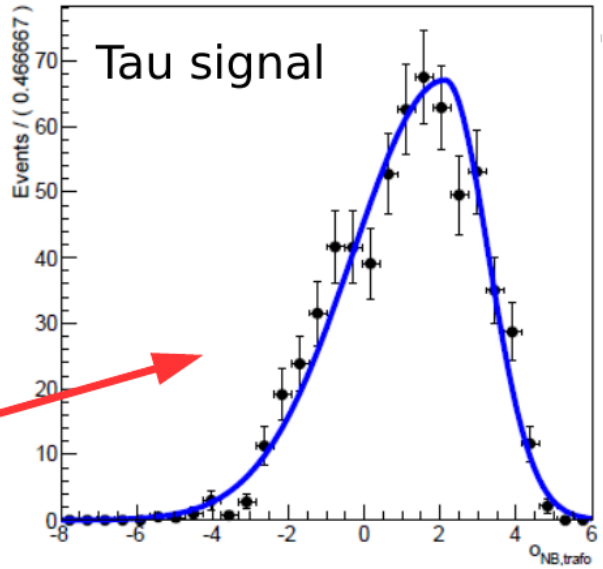
- Signal: tau signal
- Background: D^{**}, wrong charge CF, wrong lepton, D_s, rest

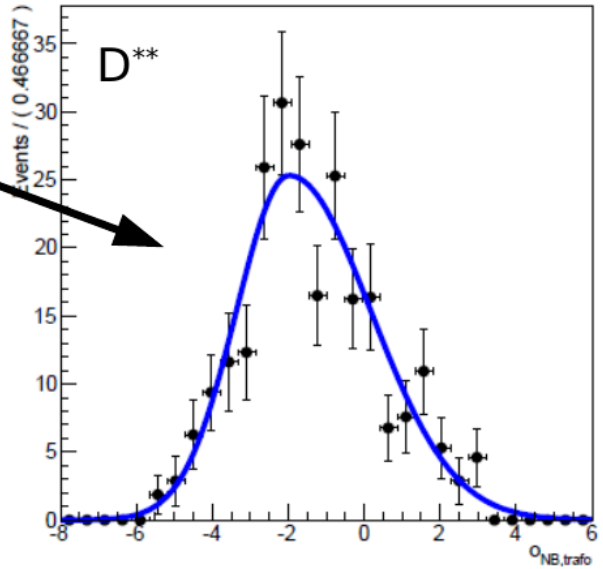
Input variables:

- M^2_{miss}
- E_{ECL}: sum of energies of clusters not assigned to B_{sig} or B_{tag}
  → Most powerful variable
- Momentum transfer q^2 and lepton momentum p_ℓ^*
  → Correlated with M^2_{miss}
- Number of unassigned π^0 with $|S_{\gamma\gamma}| < 5$
- Cos of angle between $D^{(*)}$ momentum and vertex direction
- Decay channel identifiers

O'_{NB}



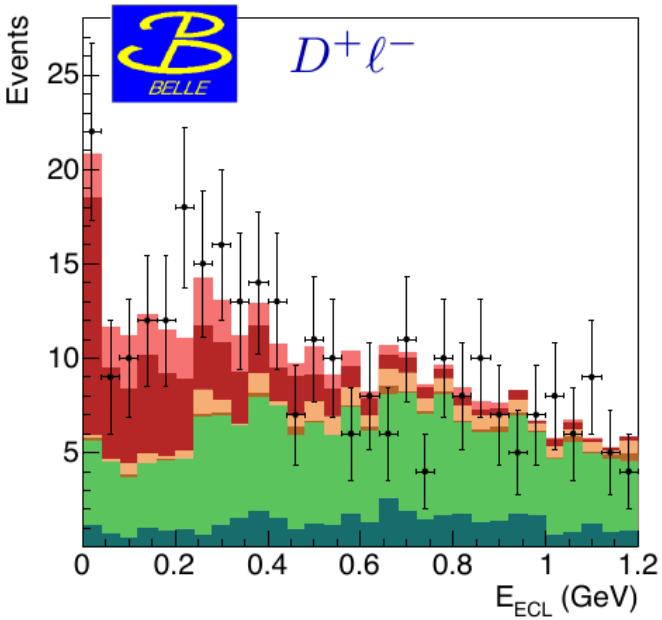


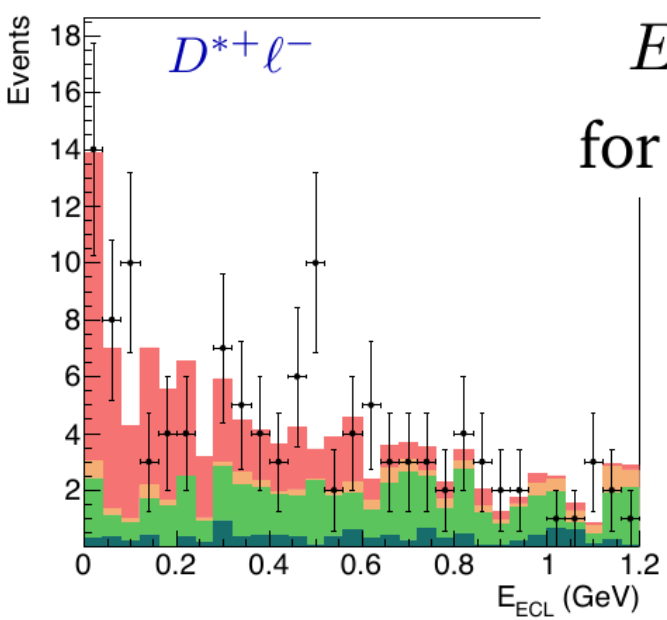


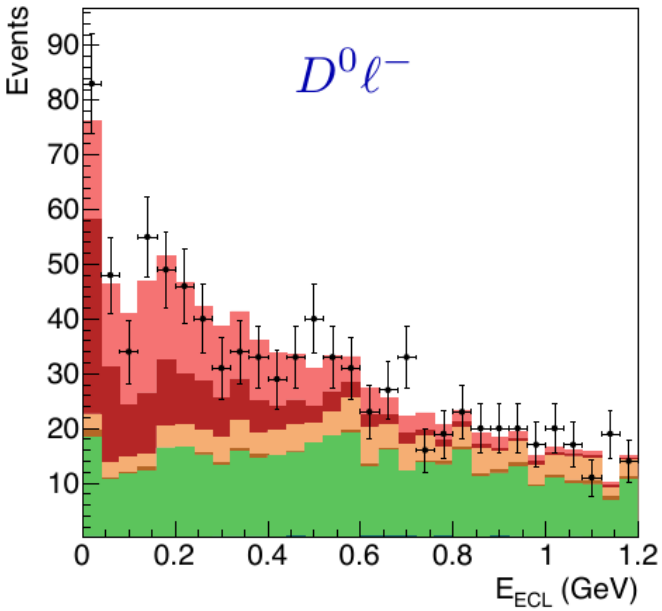
Transformation of the neural net output (o_{NB}) for easy parametrization:

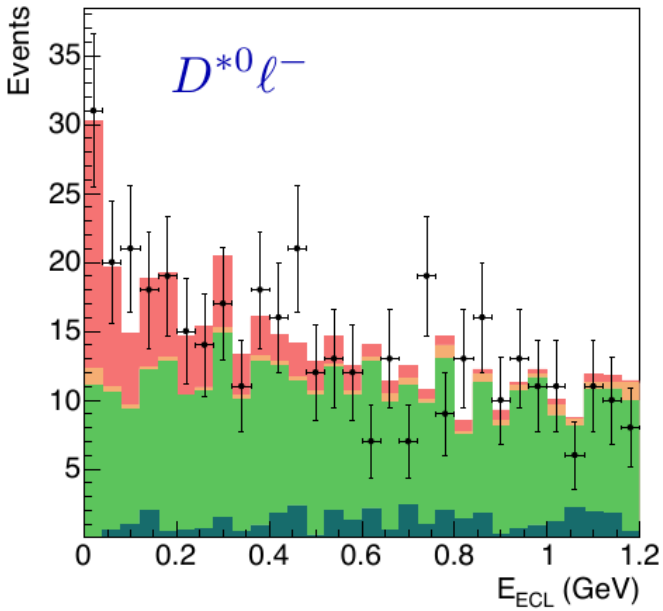
$$o'_{\mathrm{NB}} \equiv \ln \frac{o_{\mathrm{NB}} - o_{\mathrm{min}}}{o_{\mathrm{max}} - o_{\mathrm{NB}}}$$

$B \to D^{(*)}\tau\nu$ projection: $E_{\rm ECL}$









$E_{\rm ECL}$ projections for $M^2_{\rm miss} > 2{\rm GeV}^2$

- B→ D*τν
- B→ Dτν
- B→ D*lν
- B→ Dlν
- other BG
- B→ D**lν